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DAVID W TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CE--ETC F/G 13/2
PROCESSING OF RAW SEWAGE BY ULTRA-FILTRATION.(U)
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PROCESSING OF RAW SEWAGE BY ULTRAFILTRATION

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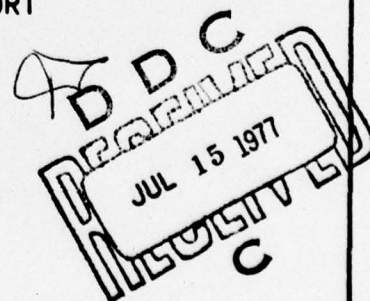
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PROCESSING OF RAW SEWAGE
BY ULTRAFILTRATION

By
L. R. Harris and C. M. Adema

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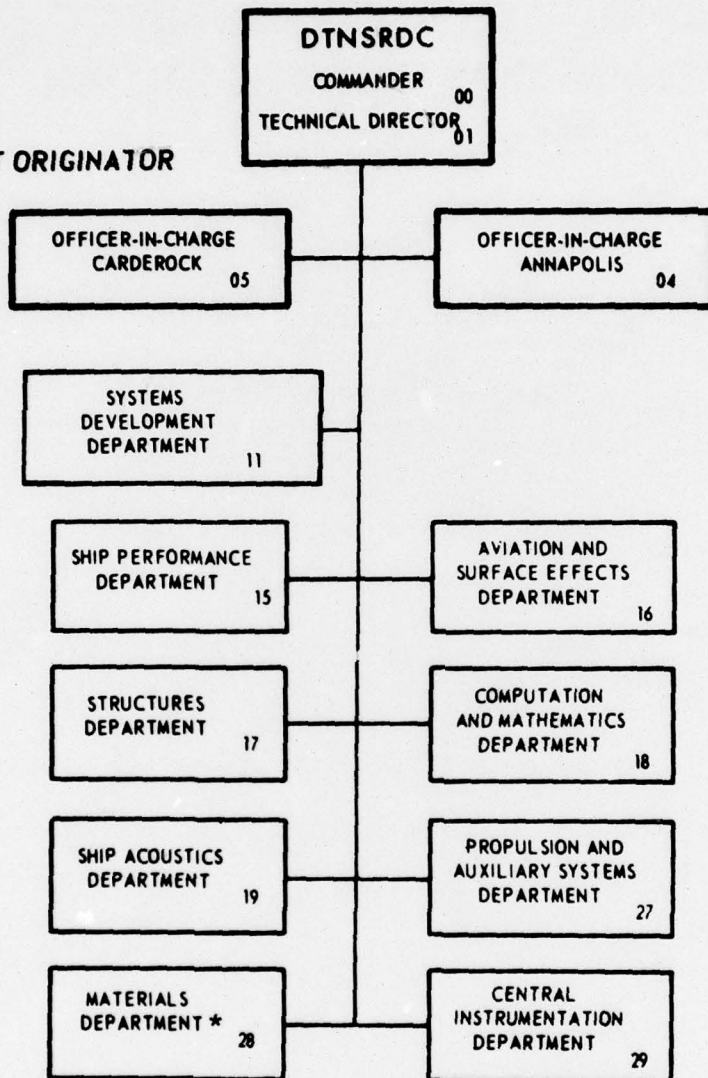


April 1977

Report MAT-77-79

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER MAT-77-79	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) PROCESSING RAW SEWAGE BY ULTRA-FILTRATION		5. TYPE OF REPORT & PERIOD COVERED
7. AUTHOR(s) L. R. Harris and C. M. Adema		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS David W. Taylor Naval Ship R&D Center Annapolis, Maryland 21402		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Program Element 63721N Task Area S0401 Work Unit 2861-137
11. CONTROLLING OFFICE NAME AND ADDRESS David W. Taylor Naval Ship R&D Center Bethesda, Maryland 20084		12. REPORT DATE April 1977
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		13. NUMBER OF PAGES 16
15. SECURITY CLASS. (of this report) Unclassified		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report) Research and development rept.		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Ultrafiltration Spiral wound Fecal coliform Microfiltration Plate and frame Waste management Tubular Raw sewage Hollow fiber Suspended solids		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) To meet discharge regulations for marine sanitation devices, the Navy has established by the Environmental Protection Agency and the U. S. Coast Guard, the Navy has been evaluating various state-of-the-art processes and techniques. One of the newer technologies is ultrafiltration, a pressure-driven membrane process. A microfiltration and nine ultrafiltration systems were evaluated (Over)		

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for their effectiveness in processing raw sewage while producing an effluent that could meet the discharge requirements. Four filtration configurations: tubular, hollow fiber, spiral wound, and plate and frame were tested. Pretreatment and cleaning requirements for each system were established. Because of operating problems not all systems were evaluated for the same time period. Each system was compared in terms of relative flux decline, maintenance, rejection of fecal coliform, and suspended solids. All systems produced an effluent, meeting the January 1980 effluent standard requirement for suspended solids content; (less than 150 milligrams per litre); while all but two met the requirement for fecal coliform bacteria density. (less than 200 fecal coliform bacteria per 100 millilitres). It was recommended that further tests should be conducted with a non-cellulosic, 1-inch (2.5 centimetre) inside diameter tubular membrane and a hollow fiber membrane system, coupled to a biological oxidation process and compared with a plate and frame membrane design, which has been previously evaluated in this mode.

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ADMINISTRATIVE INFORMATION

This work was accomplished under Program Element 63721N,
Task Area SO401, Work Unit 2861-137.

LIST OF ABBREVIATIONS AND SYMBOLS

°		
A	-	- Angstrom (10^{-8} cm)
°C		- degree Celsius
CHT		- collection, holding, and transfer
cm		- centimetre
EPA		- Environmental Protection Agency
MSD		- marine sanitation device
°F		- degree Fahrenheit
ft ²		- square foot
ft/sec		- feet per second
gal/day		- gallon per day
gal/ft ² /day		- gallon per square foot per day
gal/min		- gallon per minute
HP		- horsepower
hr		- hour
k		- prefix indicating 10^3
M		- prefix indicating 10^6
kw		- kilowatt
l/min		- litre per minute
m ³ /day		- cubic metre per day
mg/l		- milligram per litre
ml		- millilitre
mm		- millimetre
m ³ /m ² /day		- cubic metre per square metre per day
m/sec		- metre per second
Pa		- pascal
pH		- negative logarithm of the hydrogen ion concentration
psi		- pound per square inch
RO		- reverse osmosis
UF		- ultrafiltration
km		- kilometre

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ABSTRACT

To meet discharge regulations for marine sanitation devices, established by the Environmental Protection Agency and the U. S. Coast Guard, the Navy has been evaluating various state-of-the-art processes and techniques. One of the newer technologies is ultrafiltration, a pressure-driven membrane process. A microfiltration and nine ultrafiltration systems were evaluated for their effectiveness in processing raw sewage while producing an effluent that could meet the discharge requirements. Four filtration configurations: tubular, hollow fiber, spiral wound, and plate and frame were tested. Pretreatment and cleaning requirements for each system were established. Because of operating problems not all systems were evaluated for the same time period. Each system was compared in terms of relative flux decline, maintenance, rejection of fecal coliform, and suspended solids content. All systems produced an effluent, meeting the January 1980 effluent standard requirement for suspended solids (less than 150 milligrams per litre); while all but two met the requirement for fecal coliform bacteria density (less than 200 fecal coliform bacteria per 100 millilitres). It was recommended that further tests should be conducted with a noncellulosic, 1-inch (2.5 centimetre) inside diameter tubular membrane and a hollow fiber membrane system, coupled to a biological oxidation process and compared with a plate and frame membrane design which has been previously evaluated in this mode.

INTRODUCTION

OBJECTIVE

To evaluate membrane filter systems in the tubular, hollow fiber, spiral wound, and plate and frame configurations for their effectiveness in treating raw sewage. This investigation will determine UF's* potential, as a shipboard waste management system, for complying with the January 1980 EPA-Coast Guard MSD discharge regulations for vessels.

*Definition of abbreviations appears on page i.

BACKGROUND

Many Navy ships are being backfitted with CHT systems as an interim measure to meet sewage discharge regulations. These regulations, established by the EPA and the U. S. Coast Guard for MSD's, state that on or after 30 January 1977, "the effluent have a fecal coliform bacteria count not greater than 1000 per 100 ml and no visible floating solids" and that by 30 January 1980, "the effluent have a fecal coliform bacteria count not greater than 200 per 100 ml and suspended solids not greater than 150 mg/l."¹ Although the CHT capacity is intended to provide up to a 12-hour holding capability, there are a number of anticipated problems;

- Many Navy ships lack the space for a tank with a 12-hour retention time, so that substantially smaller holding capacities exist.

- There is a need for manhandling of hoses with consequent problems of spill and noisomeness.

- Nesting of ships requires pump out hosing and connections to cross other ships.

- Frequent movement of ships at a Navy port complex to different service piers requires disconnect/reconnect operations.

- Ships unable to move close to pier side pump out facilities must be served by dedicated barges, creating barge traffic superimposed on regular ship traffic.

- Many ports of call, domestic and foreign, cannot be expected to have pump out facilities.

- Addition of wastewaters other than blackwater to the CHT will cause its capacity to be exceeded rapidly unless immediate pump out facilities are available.

These difficulties can be overcome by providing ships with a wastewater concentrating system that is simple to install and operate. Such a system would concentrate the solids, return them to an aerated holding tank, and discharge overboard an effluent meeting the fecal coliform and suspended solids regulations.

¹Superscripts refer to similarly numbered entries in the Technical References at the end of the text.

One approach the Navy is considering is concerned with statically screening the solids from sewage, followed by disinfection of the liquid fraction using an ultrasonic device possibly in combination with a hypochlorite solution. Another of the newer technologies the Navy has been evaluating which shows promise in satisfying the regulations is UF and is the subject of this report. This pressure-driven membrane process:

- Operates at low pressure, generally between 10-100 psi (70-700 kPa).
- Offers the ability to separate macromolecules, colloids, bacteria, and suspended solids from solution without requiring a phase change during the separation of solute and solvent.
- Requires only one prime moving device, a circulation pump for maintaining pressure and shear action in the membrane system.

In addition to producing a permeate (effluent), UF also forms a concentrate (retentate) which may be 2-50 fold more concentrated than the original wastewater. Biological oxidation is one method for treating this concentrated wastewater. However, at the increased concentrations, the concentrate may be disposed of, alternatively, by incineration, either land-based or ship-board. Moreover, the capacity of the ship's CHT tanks is extended 2-50 fold, allowing the ship to traverse or maneuver within the navigable and contiguous zones without discharging sewage, or to come into port for a weekend without having to hook up sewage discharge lines. Once the ship transits the restricted zone (0-3 miles), [0-4.8 km], the concentrated sewage may be legally pumped overboard.

The initial investigations employing membrane technology for treating domestic sewage were limited to RO,²⁻¹¹ where pressures of 1500 psi (10.5 MPa) were required. In these studies, primary or secondary sewage effluent was treated by RO. One RO program continues.¹² Although RO technology was developed in the late 1950's, UF (an outgrowth of RO) did not become a commercially available process until the late 1960's. The earliest reported investigations with UF for treating sewage utilized the Dorr Oliver membrane system.¹³⁻¹⁶ Several prototype systems based on this membrane, coupled with an activated sludge process, continue to operate. The Navy has also investigated the biological ultra-filtration concept for shipboard waste management.¹⁷ Other reported investigations with sewage have been concerned with cross flow filtration¹⁸⁻²¹ (analogous to UF) and microfiltration,²²⁻²³ both dependent upon the formation of dynamic membranes.

However, these systems are still in the research and development stage. Currently, one commercial application uses UF as part of a recirculating toilet wastewater treatment system where the membrane filter removes both coliform bacteria and suspended solids.²⁴

INVESTIGATION

TEST AND EVALUATION

A test and evaluation schedule was setup so that each of the candidate systems would be evaluated with raw sewage for 100 hours. Pretreatment requirements were to be established as well as the frequency of cleaning operations and the stability of membrane flux (gallons per square foot per day) [cubic metre per square metre per day].

DESCRIPTION OF SYSTEMS

All systems evaluated consisted of UF membranes with the exception of one, identified as tubular VI, which is a micro-filtration tube. A summary of the descriptive characteristics of each candidate system appears in table 1. Table 2 is a summary of the operating limits of the modules.

TABLE 1
DESCRIPTIVE CHARACTERISTICS OF CANDIDATE
SYSTEM MODULES

Membrane Designation	Membrane Composition	Nominal Channel Height,		Effective** Surface Area		Molecular Weight Cutoff	Apparent Pore Diameter, A
		Mils	mm	Ft ²	M ²		
Hollow Fiber I	Noncellulosic Polymer	20	0.5	30	2.8	80,000	80
Hollow Fiber II	Noncellulosic Polymer	45	1.1	15	1.4	50,000	50
Plate and Frame	Noncellulosic Polymer	125	3.1	2	0.1	18,000	30-50
Tubular I	Noncellulosic (Inorganic)	250	6.3	36.3	3.4	35,000	50-75
Tubular II*	Noncellulosic (Inorganic)	250	6.3	36.3	3.4	25,000	25-50
Tubular III	Cellulosic	1000	25	23.1	2.1	20,000	50
Tubular IV	Noncellulosic Polymer	1000	25	23.1	2.1	20,000	50
Tubular V	Noncellulosic Polymer	1000	25	7.7	0.7	20,000	50
Tubular VI*	Noncellulosic Polymer	152	3.8	32.8	3.1	-	10,000-20,000
Spiral Wound	Noncellulosic Polymer	* 60	1.5	30	2.8	20,000	50
*All candidate systems investigated were UF membranes with the exception of tubular VI which is a microfiltration tube.							
**Effective membrane surface area used in this investigation							

TABLE 2
MODULE OPERATING LIMITS

Membrane Designation	Maximum Temperature		Maximum Pressure		pH Range
	°F	°C	psig	kPag	
Hollow Fiber I	122	50	25	175	1.5-13
Hollow Fiber II	122	50	25	175	1.5-13
Plate and Frame	122	50	75	525	2.5-10.5
Tubular I	200	93	600	4200	1-14
Tubular II	200	93	600	4200	1-14
Tubular III	130	54	60	420	4-9
Tubular IV	100	71	60	420	2-12
Tubular V	180	82	60	420	2-13
Tubular VI*	93	35	16	102	3-12
Spiral Wound	180	82	60	420	2-13

*Microfiltration tube

METHODS

All filtration modules were first evaluated with tap water to establish an initial water flux. Following this test, each system was then evaluated with raw sewage. Table 3 summarizes the operating parameters of each system.

TABLE 3
OPERATING PARAMETERS USED FOR CANDIDATE MODULES

Membrane Designation	Average Operating Pressure,		Module Circulating Rate,		Linear Velocity,		Pretreatment Requirement	Operation, Hr	Power Requirements*	
	psig	kPag	gal/min	l/min	ft/sec	m/sec			Hp	kw
Hollow Fiber I	14	98	7	27	3.6	1.1	Required	0.5	(Module plugged)	
Hollow Fiber II	16	112	20	76	3.7	1.1	Required	100	0.19	0.14
Plate and Frame	31	217	45	170	6.0	1.8	Required	100	5.2	3.9
Tubular I	42	294	300	1136	13.1	4.0	Required	51	2.7	2.0
Tubular II	42	294	300	1136	13.1	4.0	Required	23	2.0	1.5
Tubular III	23	161	210	795	13.9	4.2	None	100	3.9	2.9
Tubular IV	34	238	210	795	13.9	4.2	None	100	2.0	1.5
Tubular V	40	280	210	795	13.9	4.2	None	100	1.9	2.3
Tubular VI**	13	91	100	379	7.0	2.1	Required	170	0.8	0.6
Spiral Wound	29	203	85	322	10.2	3.1	Required	0.25	(Module plugged)	

Note: Temperature held constant at 80° F (27° C).
 *Based on processing 1000 gal/day (3.8 m³/day) sewage without pretreatment accessories.
 **Microfiltration tube.

Figure 1 is a schematic of the general UF test loop used to evaluate all filtration modules. Raw sewage (blackwater) obtained from an office complex at the Center was either directly collected in the feed tank or pretreated with a 150 mesh (105 μm) vibrating screen; the liquid fraction was directed to the feed tank while the solids were collected in a separate tank. Either raw or pretreated sewage was continuously added to the feed tank. Concentrate from the filtration modules was returned to the feed tank while the permeate was discharged to the drain. Cooling coils were used to maintain the temperature in the feed tank at 80° F (27° C). Air was supplied to the feed tank to maintain aerobic conditions. Circulation through the filtration modules was provided by a centrifugal pump. Some of the systems required higher pressure which was obtained with either a diaphragm or progressing cavity pump in parallel with the centrifugal pump. Operating parameters were those suggested by the system's manufacturer.

Temperature within the test loop, inlet and outlet pressures of the filtration modules, circulation flow through the modules, and permeate flow rates were recorded for each system. Feed samples were obtained downstream of the circulating pump while the permeate samples were taken from the effluent line of each filtration module. Samples were analyzed for total suspended solids and fecal coliform. All analyses were performed as specified in Standard Methods.²⁵

RESULTS

The UF rate data of each system treating raw sewage is shown graphically in figure 2. Table 4 is a summary of the data shown in figure 2. Because of operating problems not all systems were evaluated for a total of 100 hours.

TABLE 4
VARIATION OF FLUX WITH TIME

Membrane Designation	Initial Water Flux	Sewage Flux			
		1 hr	10 hr	50 hr	100 hr
Hollow Fiber I	260 (10.6)	Plugged			
Hollow Fiber II	150 (6.1)	22 (0.9)**	26 (1.1)**	21 (0.9)**	22 (0.9)**
Plate and Frame	221 (9.0)	14 (0.6)	4 (0.2)	6 (0.2)**	6 (0.2)**
Tubular I	115 (4.7)	55 (2.2)	33 (1.3)**	21 (0.9)**	
Tubular II	99 (4.0)	52 (2.1)	47 (1.9)**	[23 hr]	
				37 (1.5)**	
Tubular III	59 (2.4)	33 (1.3)	27 (1.1)	28 (1.1)	23 (0.9)
Tubular IV	126 (5.1)	71 (2.9)	64 (2.6)	51 (2.1)	44 (1.8)
Tubular V	211 (8.6)	62 (2.5)	71 (2.9)	42 (1.7)	59 (2.4)
Tubular VI*	247 (10.0)	19 (0.8)	16 (0.7)	13 (0.5)	15 (0.6)
Spiral Wound	230 (9.7)	Plugged			

*Microfiltration tube.

**Data taken within 1 hour of cleaning operation.

Note: Units of all figures are gal/ft²/day (m³/m²/day) at 27° C.

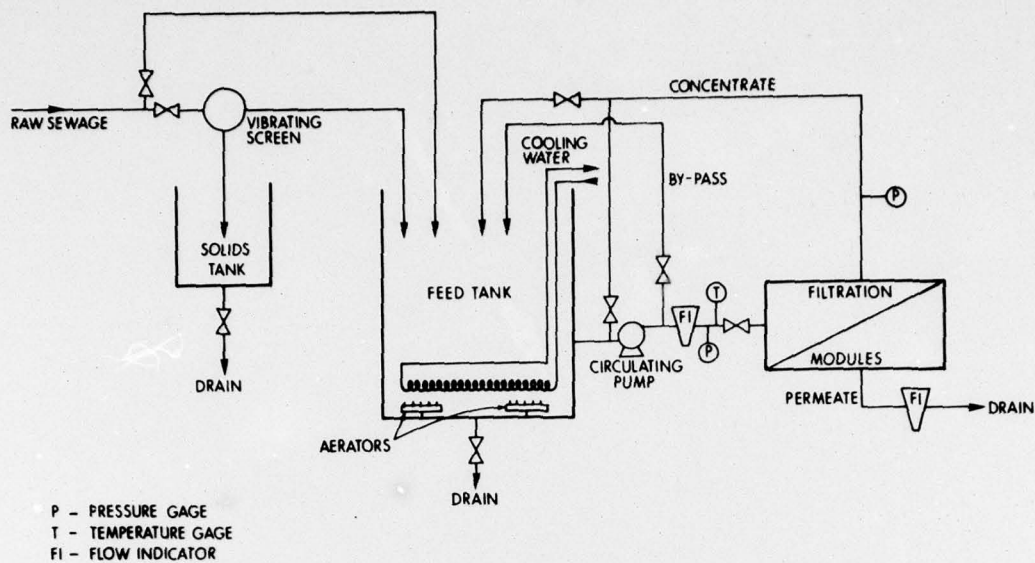


Figure 1
Ultrafiltration Test System

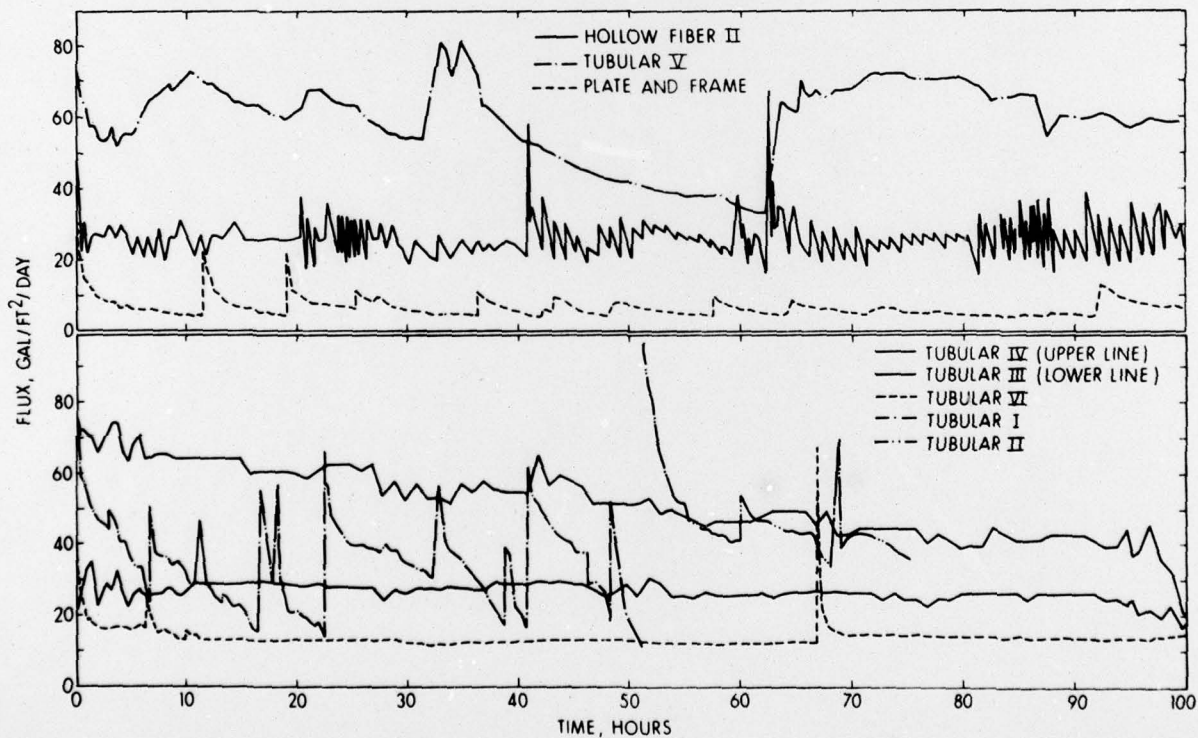


Figure 2
System's Performance with Raw Sewage

Table 5 summarizes the separation effectiveness of each candidate system in terms of the required criteria for suspended solids and fecal coliform. The permeate of each module was initially clear and colorless but gradually developed an amber color which remained for the rest of the test. No odor was detected for any of the permeate samples throughout their respective tests. However, if the permeate was collected and not aerated for several hours, a faint ammonia-like odor was detected.

TABLE 5
SUMMARY OF FEED AND PERMEATE QUALITY

Membrane Designation	Average Total Suspended Solids (mg/l)		Fecal Coliform Bacteria (No./100 ml)	
	Feed	Permeate	Feed Range	Average Permeate
Hollow Fiber II	400	5.0	1.6E6*-7.0E8	40
Plate and Frame	220	3.0	1.0E5 -6.5E8	<10
Tubular I	2200	2.0	6.9E6 -3.9E8	19
Tubular II	3250	5.0	4.5E5 -9.4E9	33
Tubular III	3540	12.0	1.4E6 -1.5E9	1.2E4
Tubular IV	3540	11.0	1.4E6 -1.5E9	160
Tubular V	5170	47.0	4.3E3 -4.7E9	70
Tubular VI**	1370	21.0	2.1E5 -2.0E10	1.0E5
		≤150***		≤200***
*FORTRAN exponent form: 1.6E6 = 1.6 x 10 ⁶ .				
Microfiltration tube. *1980 requirement.				

DISCUSSION OF RESULTS

Results presented in figure 2 and table 4 show the flux decline behavior of each system evaluated. Only the relative flux declines should be compared and not the absolute flux values, because each filtration module was evaluated under different operating conditions (only the temperature was constant) as required by each system's specific design. It is noted from figure 2 that only tubular systems III, IV, V, and VI showed small overall flux declines. These were the only systems that did not require any cleaning operation during their 100-hour continuous test.* Evaluation of tubular I module was terminated after 52 hours of operation because attempts to recover flux by various cleaning operations proved to be unsuccessful. A second module, tubular II, was only operated for 24 hours (52-76 hours in figure 2) but demonstrated improvement over the tubular I module.

*The tubular VI system received a cleaning which turned out to have been unnecessary.

Flux declines followed by abrupt flux increases (spikes) in turn followed by abrupt flux declines, figure 2, generally signify that a cleaning operation was performed. The less pronounced variations for tubular III, IV, and V membranes were due to scatter in flux measurements. With the exception of tubular III, IV, and V all of the filtration modules required pretreatment to complete their test. The 150 mesh (105 μ m) vibrating screen that was used proved to be satisfactory for the hollow fiber II, the plate and frame, and the tubular systems I and II if periodic cleaning was also provided. After the cleaning operation, at about 68 hours (figure 2) on the tubular VI system, testing continued for an additional 100 hours (68 hours not shown) without any change in flux. Two membrane systems, hollow fiber I and spiral wound, were found to plug irreversibly after 0.25 and 0.50 hour, respectively, even with pretreatment and repeated cleaning operations.

All filtration systems produced an effluent satisfying the suspended solids requirement (150 mg/l) and, with the exception of the tubular III and VI, all of the systems met the fecal coliform bacteria requirements (200/100 ml) for discharge from vessels. It is believed that the high coliform count for the tubular III system was due to either a leak in a module seal or a defect in one of the tubular membranes. The tubular III was tested concurrently (although at a lower pressure) with the tubular IV and consequently saw the same feed concentrations. Because the tubular VI is a microfiltration system which is more porous than the other systems evaluated, bacteria may enter the permeate during the initial minutes of testing until a dynamic membrane or dynamic plug is formed on the inside of the microfiltration tube. As a result of the excessive permeate hold up time for this module (approximately 1 hour), the bacteria are not flushed out fast enough and are able to multiply in the housing. This accounts for the large fecal coliform count in the effluent.

The steep flux decline of the tubular III and IV systems, after 92 hours of testing (figure 2), was due to concentrating the existing feed tank contents without adding any raw sewage. A suspended solids content of 4.7% was measured at the end of the run (100 hours). Flux increases for the tubular V membrane were observed at 33 and 35 hours after the system had been shut down. This suggests that decompression of the membrane due to downtime appears to produce a temporary increase in flux. The observed flux increase for the same module at about 62 hours resulted from starting the feed tank aerator which had not been operating. This indicates that aeration and the associated biological oxidation of the sewage enhances the UF process. Cleaning the plate and frame

module appears to offer only a modest performance improvement. It is observed that the flux for that unit tends to plateau at about 4.0 gal/ft²/day (0.16 m³/m²/day) without cleaning.

Cleaning operations consisted of three types, reverse flushing, backflushing, and chemical flushing. The necessity for cleaning was dependent upon the particular filtration system. Reverse flushing with tap water was used for the hollow fiber and the plate and frame units to remove fiber and concentrated solids buildup at the leading edge of each module. Backflushing from the permeate side with permeate or distilled water was used on the hollow fiber modules only. Chemical flushing included flushing with solutions of hypochlorite, detergent, detergent-enzyme, acid or base. The choice of chemical flushing agent was dependent upon the characteristics of each filtration module.

A forthcoming report will provide a more detailed comparison of the candidate systems, including comparisons of rejection of chemical and biochemical oxygen demand, power requirements, and maintenance requirements.

FINDINGS AND CONCLUSIONS

The following conclusions can be drawn from this investigation:

- Ultrafiltration is an effective process for treating raw sewage wastes in meeting the marine discharge requirement for fecal coliform bacteria and suspended solids.
- Commercially available UF systems have demonstrated their potential for effectively extending the holding time of CHT systems 2-50 fold, providing unencumbered naval operations at foreign and domestic ports of call where pump out facilities may be unavailable. Alternatively, by increasing the concentration of sewage wastes with UF, smaller capacity tanks become feasible.
- Most UF and microfiltration systems require pretreatment to remove bulk solids and fibrous materials.
- Pretreatment and cleaning operations can be minimized by selecting a filtration system capable of handling high solid concentrations such as the large flow path channel height (1-inch) [2.5 cm] tubular system.
- The feasibility of utilizing UF in a shipboard environment still has to be proven.

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MAT-77-79, April 1977